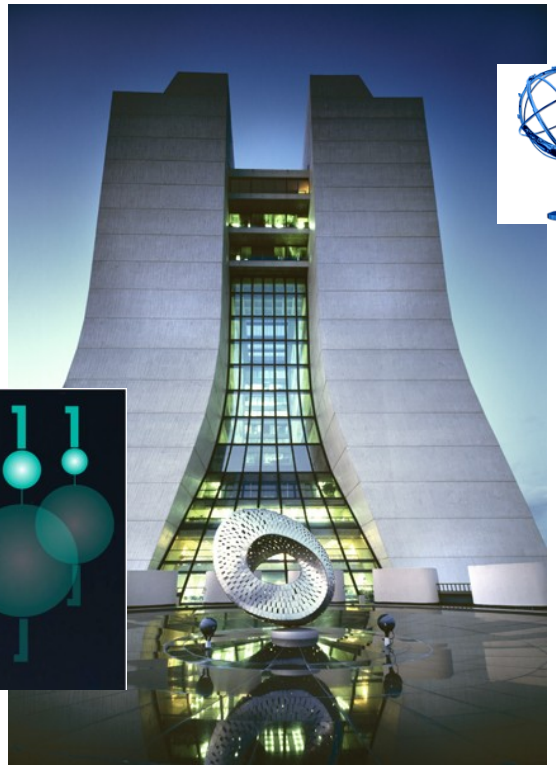
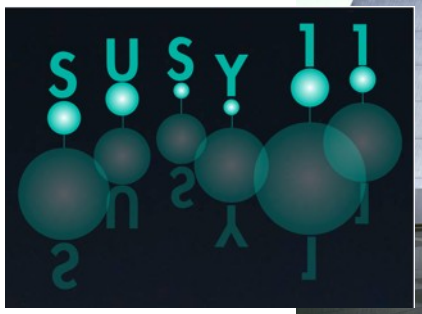
SUSY Searches at ATLAS





Wolfgang Ehrenfeld (DESY)
On behalf of the ATLAS Collaboration

Fermilab, August 30th, 2011

HELMHOLTZ ASSOCIATION

DESY

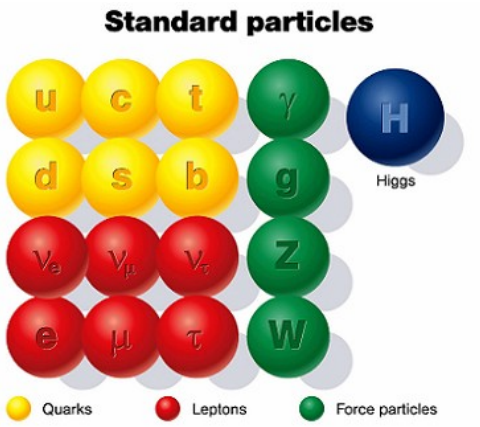
Outline

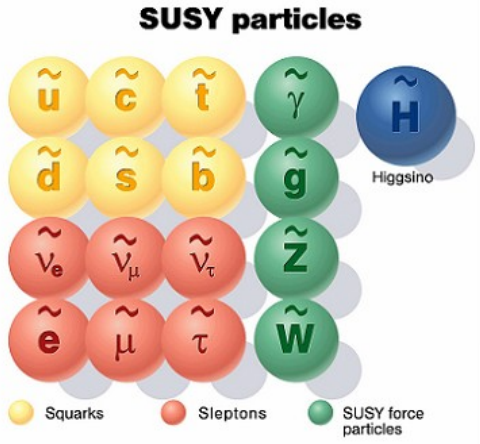
- introduction to supersymmetry
- ATLAS and LHC
- final states with missing E_T
  - jets with lepton veto
  - one and two leptons
  - b-jets
  - diphotons
- final states without missing E_T / R-parity violation
  - colored scalars
  - $e\mu$ resonance
  - displaced vertices
- summary and outlock

Supersymmetry (SUSY)

One of the most popular extensions of the SM

- SUSY postulates “superpartners” to each SM particles (same quantum numbers, but spin differs by ½) and R-parity $R = (-1)^{3(B-L)+2s}$
- if R-parity is conserved, SUSY particles are pair produced and the lightest one (LSP) is stable
- Why is SUSY popular? It answers many open questions at once:
  - allows unification of gauge couplings
  - provides a solution to the hierarchy problem: the fermion/boson contribution to the Higgs mass exactly cancel
  - if R-parity is conserved the LSP is stable and is a dark matter candidate
- but the MSSM has 124 free parameters …
  - How should we search?

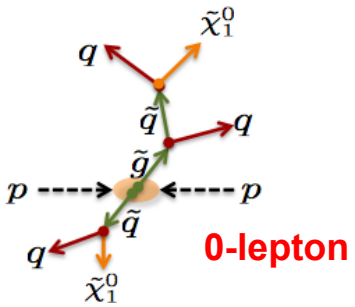


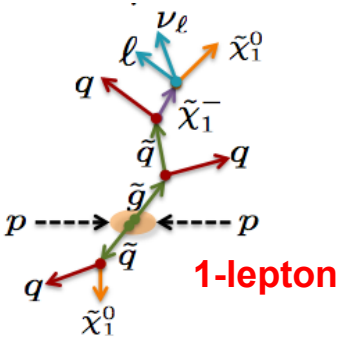


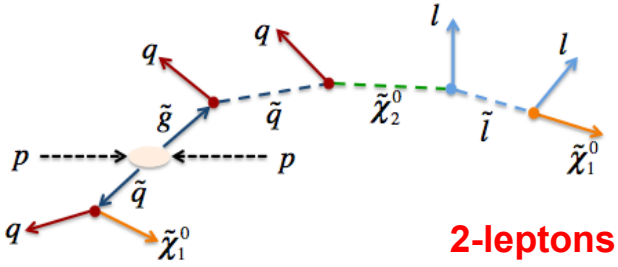
Search Strategies for SUSY

- at the LHC sparticles are pair produced
  - dominantly squarks and gluinos via the strong interaction
  - they decay via cascades into the stable LSP (neutralino or gravitino), assuming R-parity conservation
- common signature:
  - multiple, high energetic jets and transverse missing momentum
  - distinguish final states by additional particles

    zero, one, two, .. leptons (e, μ), two photons, …
    b-jets if 3rd generation squarks are lighter than other generation squarks
- incomplete event reconstruction due to LSP
  - no mass peak
    → SUSY is in the tails of the distributions
  - SM backgrounds (top, W/Z+jets, QCD) are taken from/verified in control regions







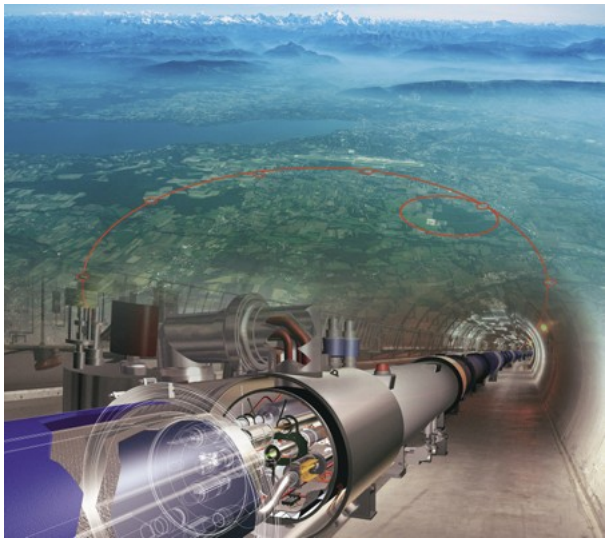
A Word on Models

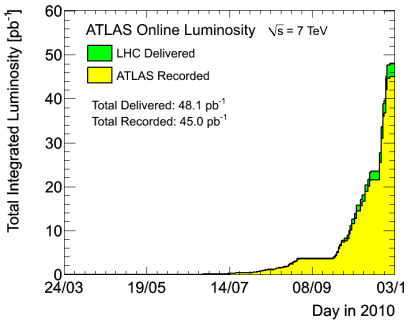
- most experimental results are interpreted in one or the other model
  - e.g. mSUGRA/CMSSM, GMSB, simplified models, …
  - the interpretation in a model give nice, colored plots
- the main experimental result is the limit on the number of signal events in the signal region (or the limit on the effective cross section)
- interpretation is straight forward but not trivial
  - signal efficiency
  - signal uncertainties
  - statistical interpretation

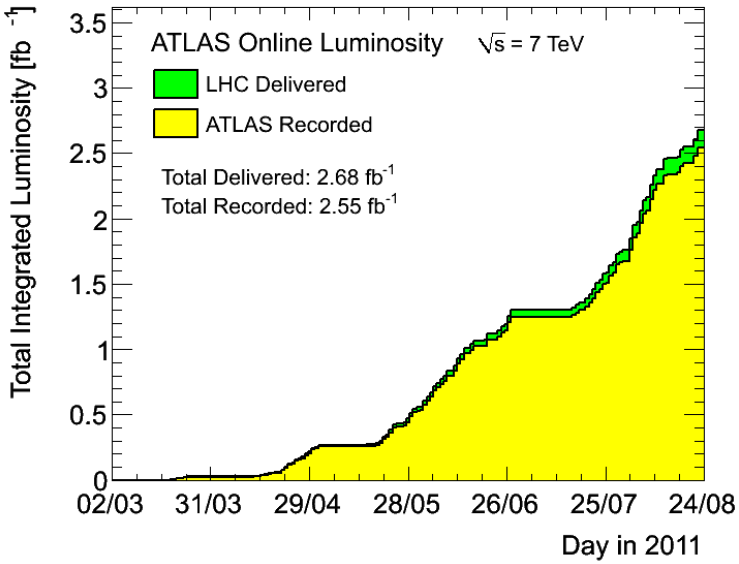
- mSUGRA/CMSSM:
  - **m_0:** common scalar mass
  - **$m_{1/2}$:** common gaugino mass
  - **A_0:** common trilinear coupling
  - **tan β:** ratio of Higgs vacuum expectation values
  - **sign(μ):** sign of SUSY Higgs potential parameter
- GMSB:
  - **Λ:** SUSY breaking scale
  - **M:** messenger mass scale
  - **N:** number of messenger fields
  - **tan β:** ratio of Higgs vacuum expectation values
  - **sign(μ):** sign of SUSY Higgs potential parameter
  - **C_{grav}:** ratio of the gravitino mass to its value at the breaking scale Λ
- Simplified models:
  - **reduced particle spectrum:** masses

The Large Hadron Collider

- pp collisions at $\sqrt{s}$ = 7 TeV
  (and PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV,
  not covered in this talk)
- LHC has performed extremely well this year:
  - 2.2 10^{33} /cm^2/s peak luminosity
  - ~ 80 pb^{-1} per day
  - 2.5 fb^{-1} delivered, thanks!
  - 50 ns bunch spacing
  - 8 collisions per crossing
- datasets considered by analysis
  - 2010: ~35 pb^{-1}
  - 2011: 0.87 – 1.34 fb^{-1}

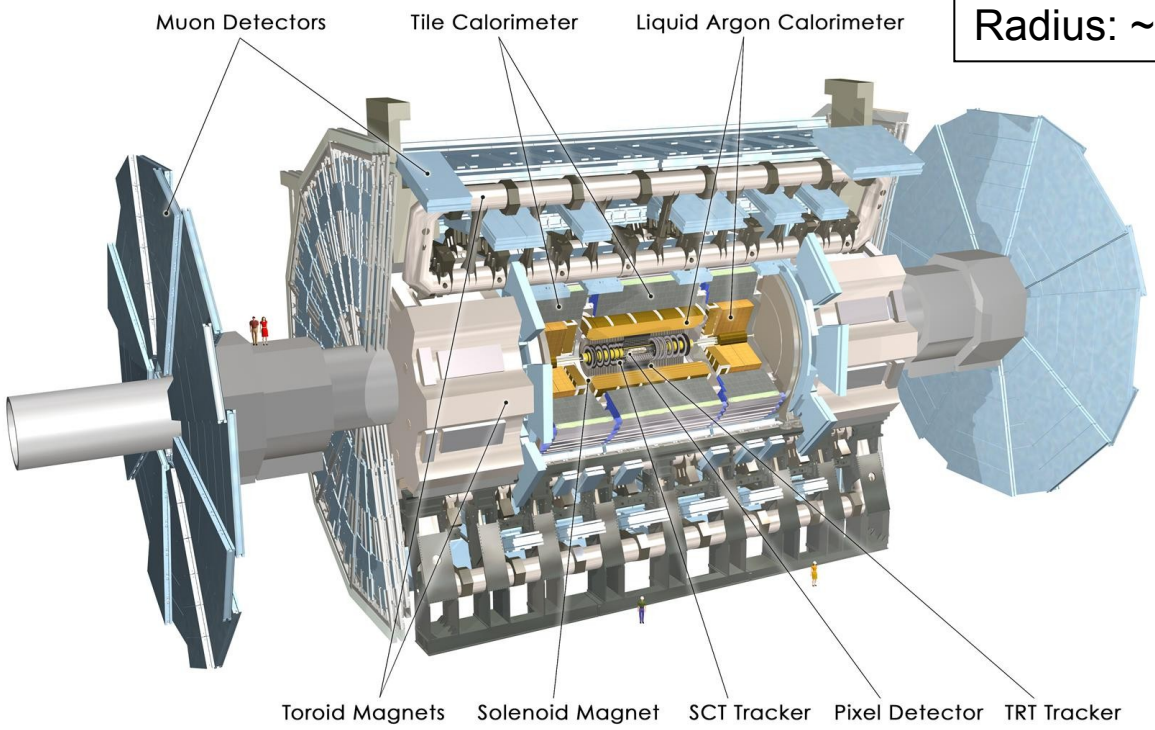






The ATLAS Detector

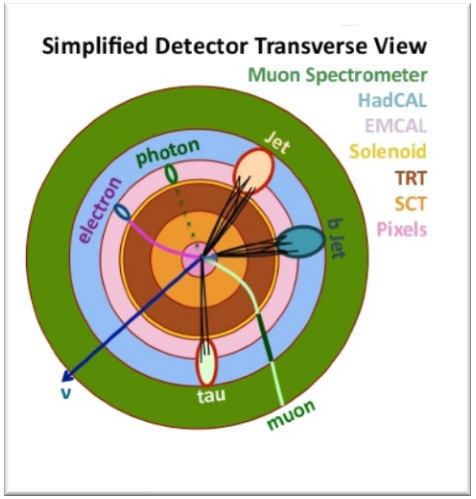
Length: ~ 46 m
Radius: ~ 12 m



~ 4π coverage in solid angle

Excellent resolution for jets, electrons, photons, muons and missing E_T

Excellent vertex reconstruction



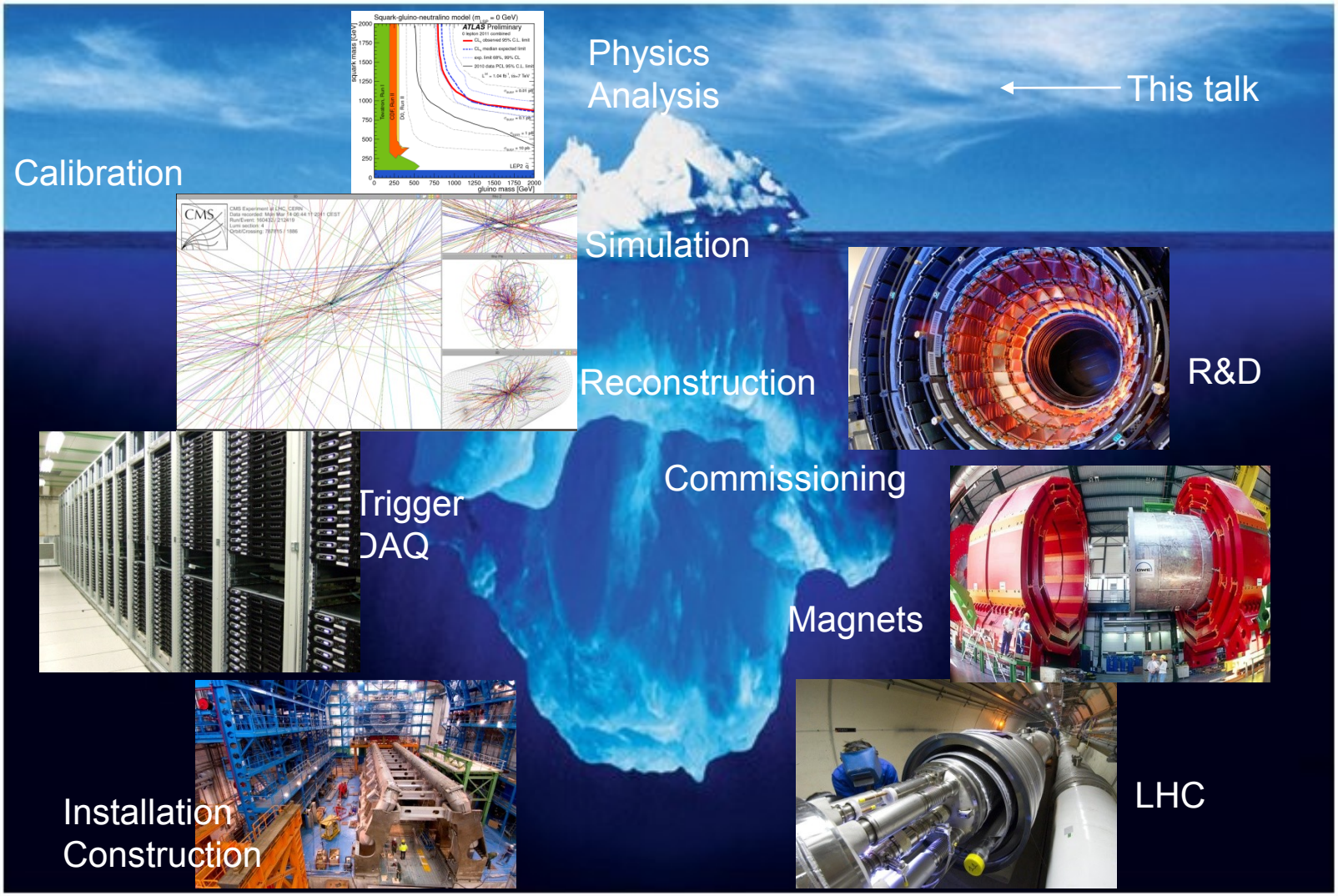
Inner Detector (ID,|η|<2.5, B=2T):
- Si Pixels, Si strips, TRT straws
- Precise tracking and vertexing, e/π separation
- $\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T\ (\text{GeV}) \oplus 0.015$

EM calorimeter(|η|<4.9):
- Pb-LAr Accordion
- e/γ trigger, identification and measurement
- $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry (|η|<4.9):
- Fe/scintillator Tiles (central), $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$
- Cu/W-LAr (fwd), $\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$
- Trigger and measurement of jets and missing E_T

Muon Spectrometer (MS,|η|<2.7) :
- air-core toroids with gas-based muon chambers
- Muon trigger and measurement with p_T resolution < 10% up ~ 1 TeV

Acknowledgements



Courtesy of Henri Bachacou

ATLAS SUSY Searches

ATLAS SUSY analyses	Publications
E_T^{miss} + jets + 0 lepton	arXiv:1102:5290 (35 pb^{-1}) [published in PLB]; ATL-CONF-2011-086 (163 pb^{-1}); preliminary (1.04 fb^{-1})
E_T^{miss} + multiple jets + 0 lepton **New**	preliminary (1.34 fb^{-1})
E_T^{miss} + jets + 1 lepton	arXiv:1102:2357 (35pb^{-1}) [PRL]; ATL-CONF-2011-090 (163 pb^{-1}); preliminary (1.04 fb^{-1})
E_T^{miss} + b jets + 0/1 lepton	arXiv:1103:4344 (35 pb^{-1}) [PLB]; ATL-CONF-2011-098 (833 pb^{-1}); ATL-CONF-2011-130 (1.03 fb^{-1})
E_T^{miss} + jets + 2 leptons (OS, SS, SF subtraction)	arXiv:1103:6214 (35 pb^{-1}) [EPJC]; arXiv:1103:6208 (35 pb^{-1}) [EPJC]; ATL-CONF-2011-091 (simplified model interpretation to SS); preliminary (1.04 fb^{-1})
E_T^{miss} + jets + >= 3 leptons	ATL-CONF-2011-039 (34 pb^{-1})
E_T^{miss} +γγ	arXiv:1107:0561 (36 pb^{-1}); preliminary (1.04 fb^{-1})
colored scalars **New**	preliminary (34 pb^{-1})
eμ resonance (RPV)	arXiv:1103:5559 (35 pb^{-1}) [PRL]; ATL-CONF-2011-109 (870 pb^{-1})
Stable hadronising squarks & gluinos	arXiv:1103:1984 (34 pb^{-1}) [published in PLB];
Heavy long-lived charged particles	arXiv:1106:4495 (37 pb^{-1}) [submitted to PLB];
Heavy medium-lived particles **New**	preliminary (33 pb^{-1})

Final States with Missing E_T

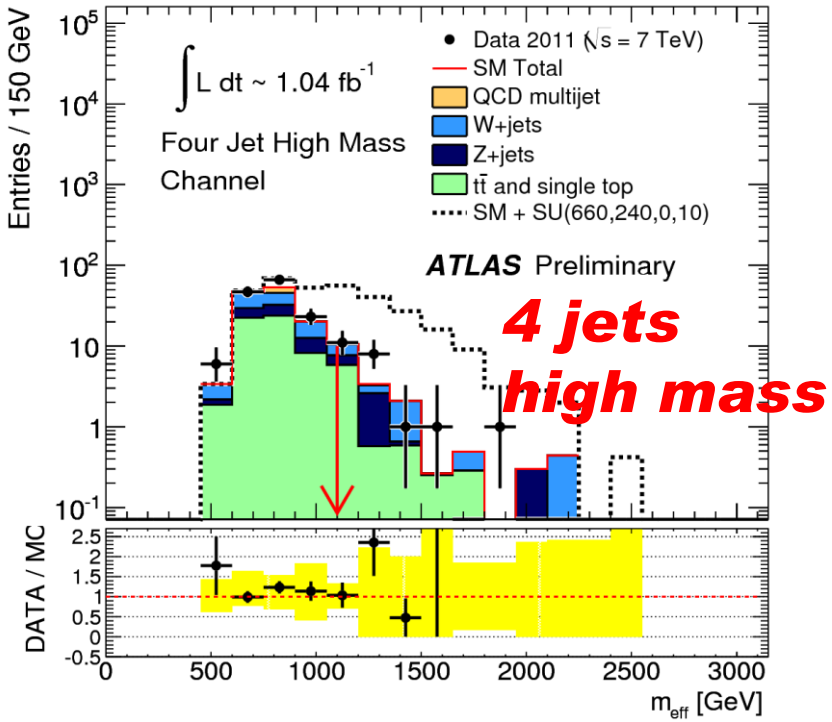
Jets + Missing E_T

Update EPS 2011

- ATLAS:
  - Select events with jets and missing E_T → veto events with p_T of e(μ) > 20(10) GeV
  - Define signal region based on effective mass: m_{eff} = H_T + missing E_T
  - optimize cut on m_{eff} and missing E_T for each jet multiplicity
  - combine 5 channels to optimize search for different topologies

H_T = scalar sum of all jet E_T

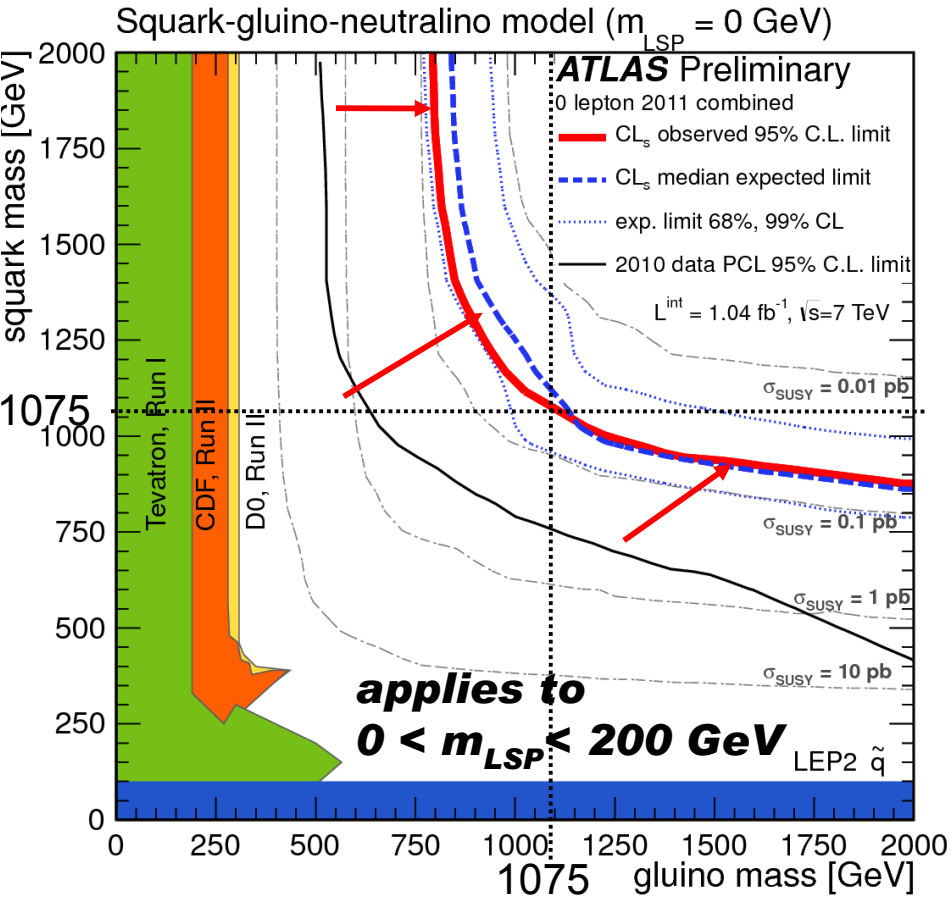
Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100



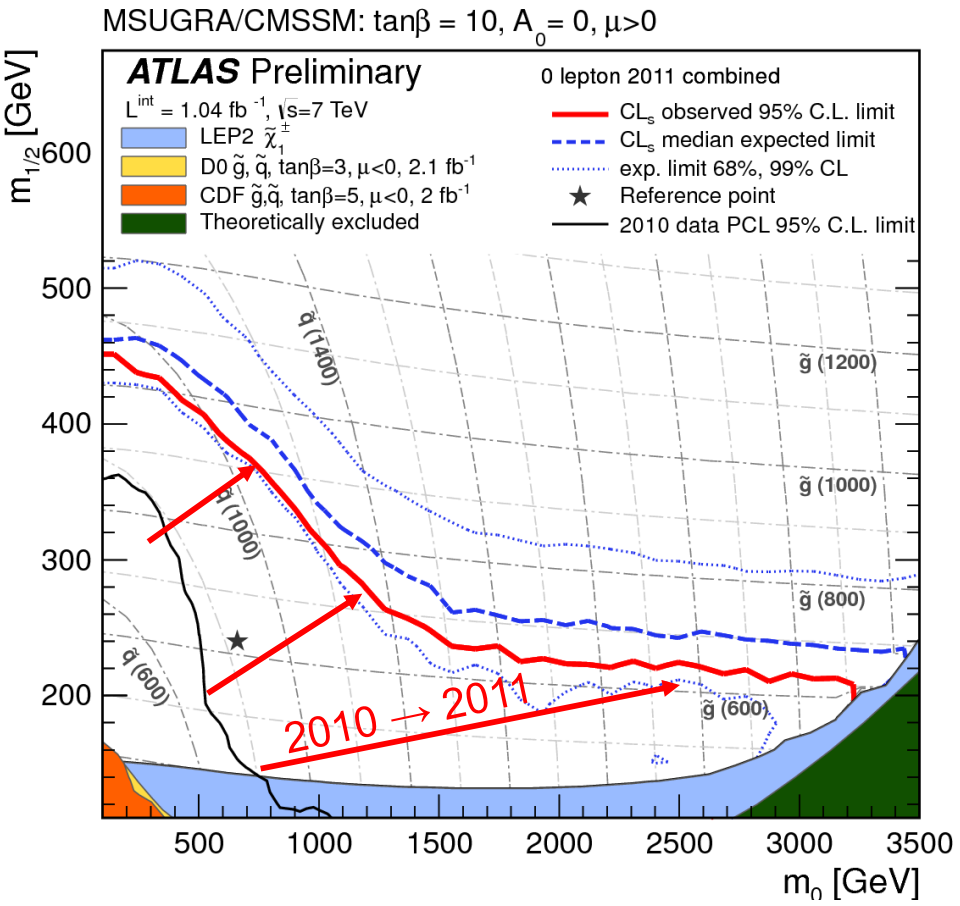
Jets + Missing E_T

Update EPS 2011

- Exclude up to ~ 1 TeV for m(squark) = m(gluino)



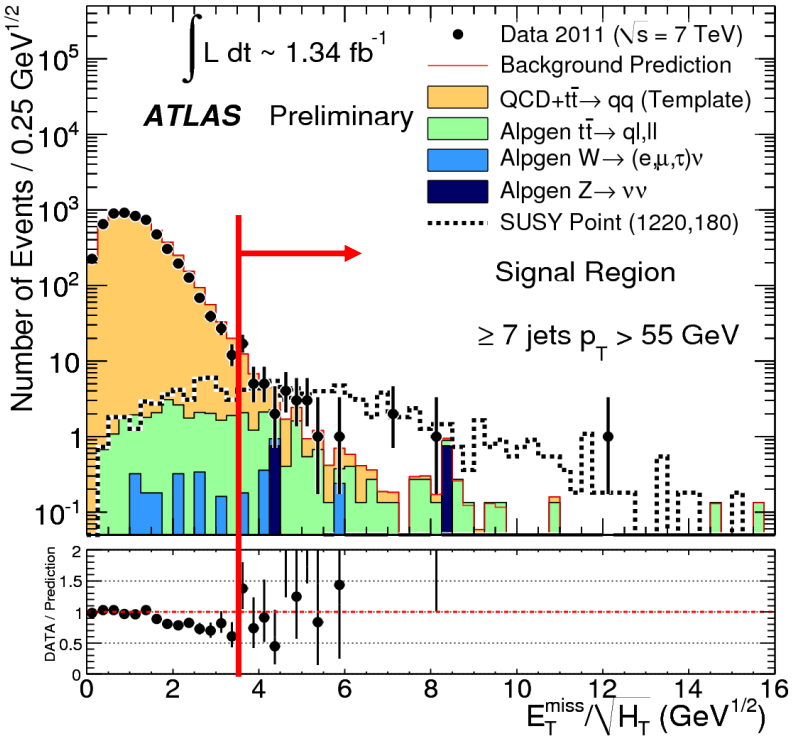
- Enormous gain since last spring: 0.035 fb^{-1} → 1 fb^{-1}

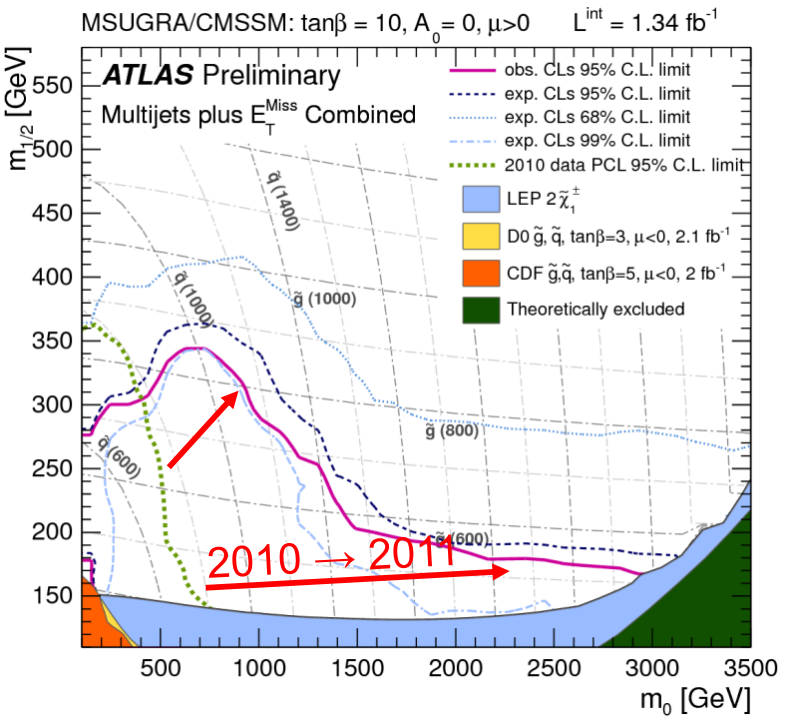


Large Jet Multiplicity + Missing E_T

New SUSY11

- use jets + missing E_T analysis and increase number of jets: **6, 7 or 8**
- QCD control region defined by lower number of jets, e.g. 7 → 6 jets
  - essential to estimate QCD background from data as MC predictions are unreliable
  - other background estimated from MC and validated in different data control regions
- signal region defined by number of jets and MET/sqrt(H_T)





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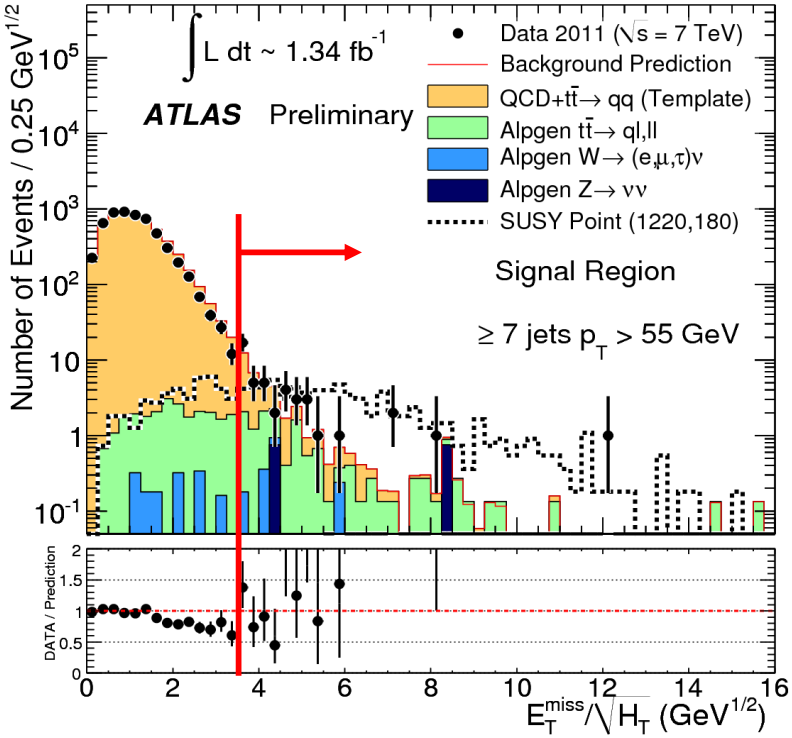
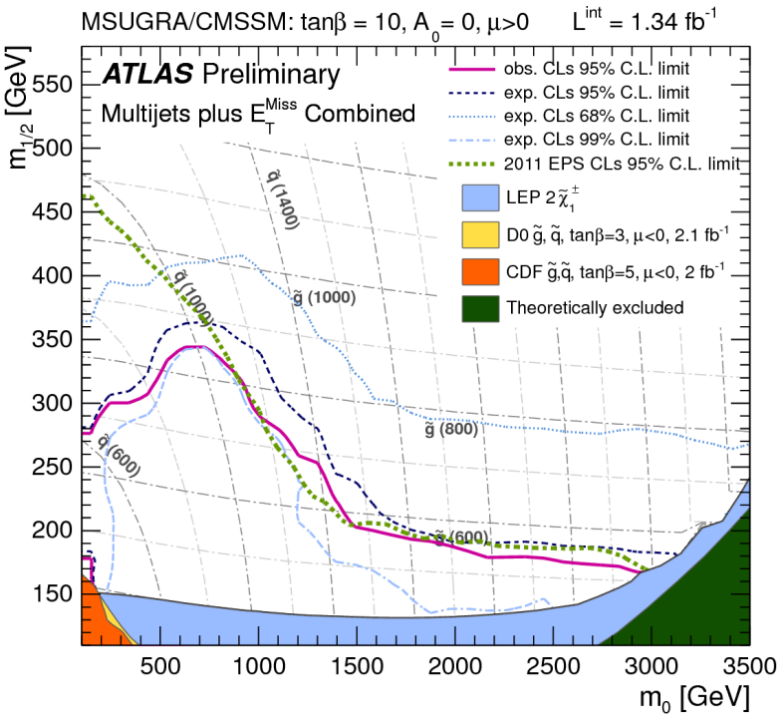
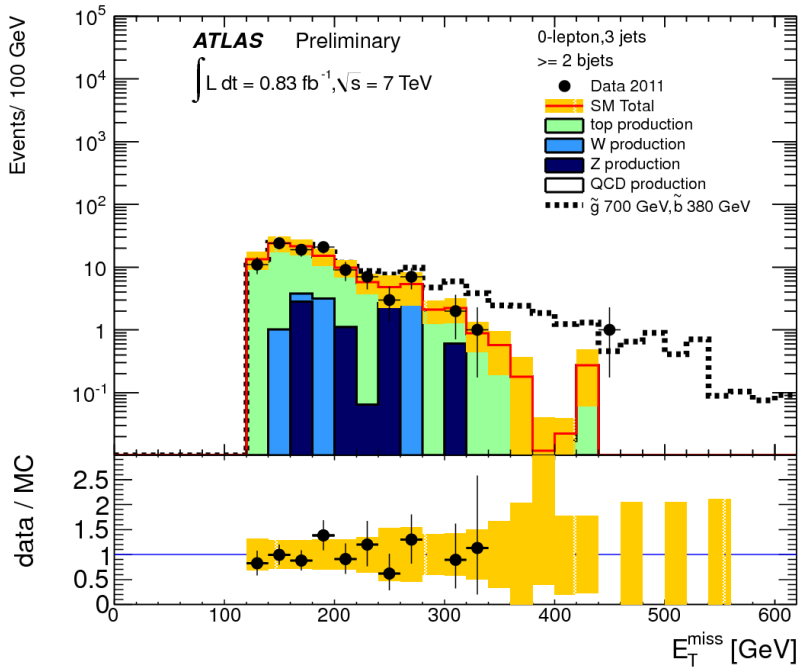




b-jets + Missing E_T

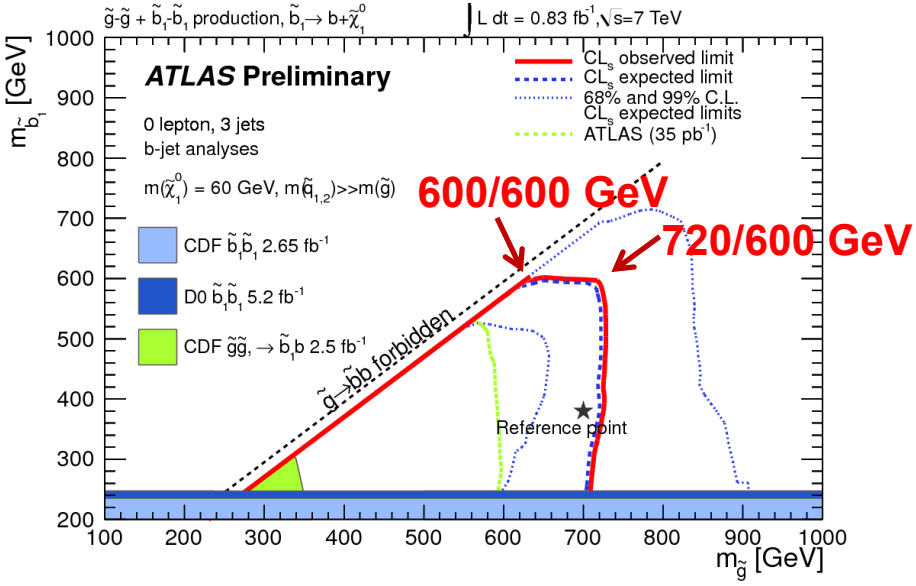
Update EPS 2011

- 3rd generation is special: has to be light to stabilize the Higgs
- selection similar to jets + missing E_T plus 1 or 2 b-tags
- define 4 signal regions / two control regions and combine them for the exclusion limit



Phenomenological MSSM:

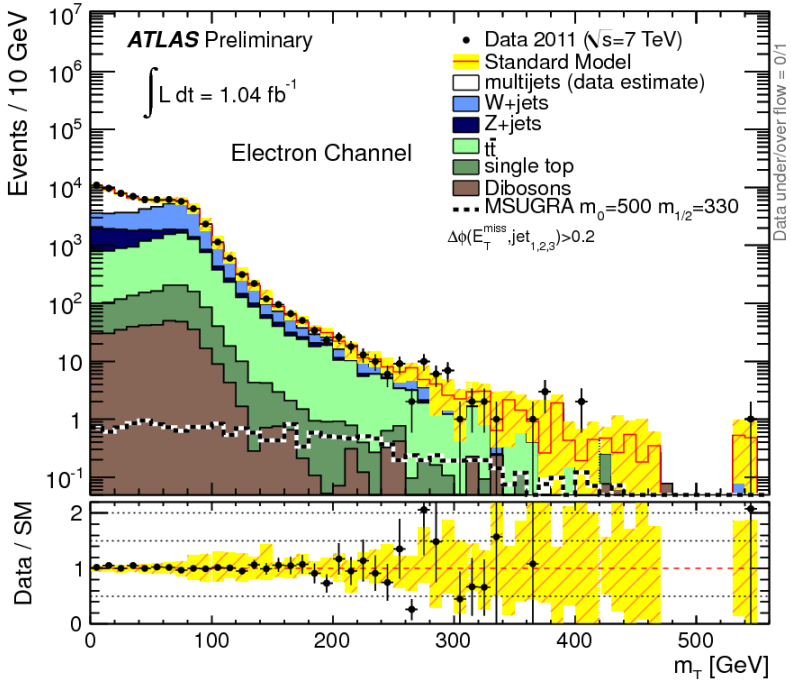
$BR(g \rightarrow b_1 b \rightarrow bb\chi^0_1) = 100\%$



One Lepton + Jets + Missing E_T

Update SUSY11

- cascades including charginos or neutralinos can lead to final states with one, two, three or more isolated leptons
- advantage: suppress QCD background, help in trigger
- analysis requires exactly 1 lepton (e: p_T > 25 GeV or μ: p_T > 20 GeV) and ≥ 3/4 jets → four signal regions



Background

- fake leptons from QCD background
  → fully data driven estimate with "loose-tight matrix method"
- non QCD background dominated by top pairs and W+jets
  → semi-data driven estimate
  - normalize MC to data in background specific CR
  - extrapolate to the signal region relying on MC shapes
  - final background estimate done performing a simultaneous likelihood fit of the different CR

$$m_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\mathrm{miss}} \cdot (1 - \cos(\Delta\phi(\vec{\ell}, \vec{E}_T^{\mathrm{miss}})))}$$

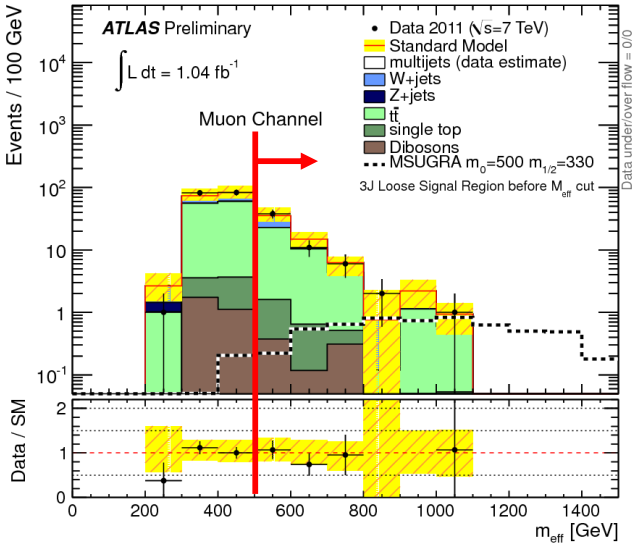
One Lepton + Jets + Missing E_T

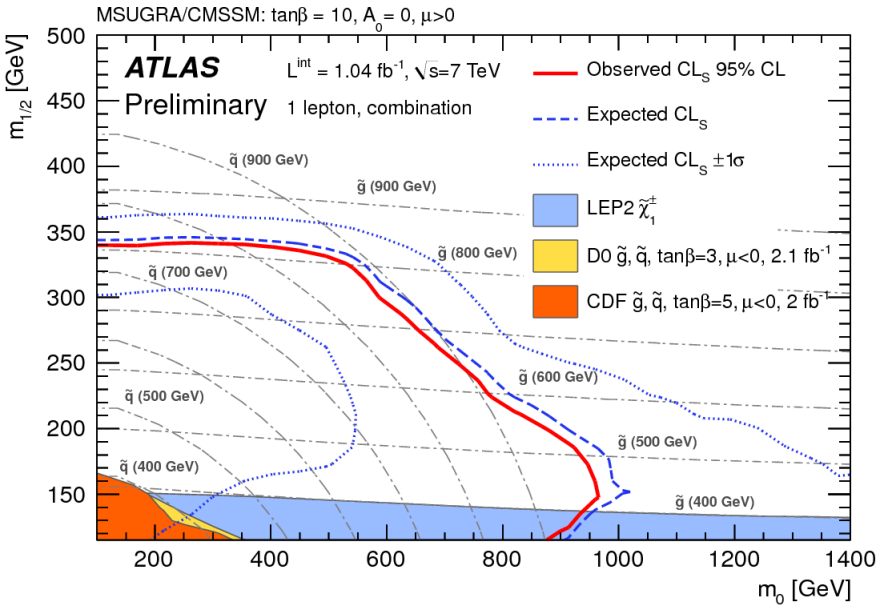
Update

SUSY11

- observed number of events in data consistent with SM
- uncertainties dominated by jet energy scale and resolution, theory and MC modeling and statistics
- interpretation in:
  - mSUGRA/CMSSM (m_0,$m_{1/2}$)-plane
  - simplified model
    gluino → chargino → neutralino
    squark → chargino → neutralino
  - bilinear R-parity violation model

For bilinear RPV see talk by Emma Pastor [9B Thu]



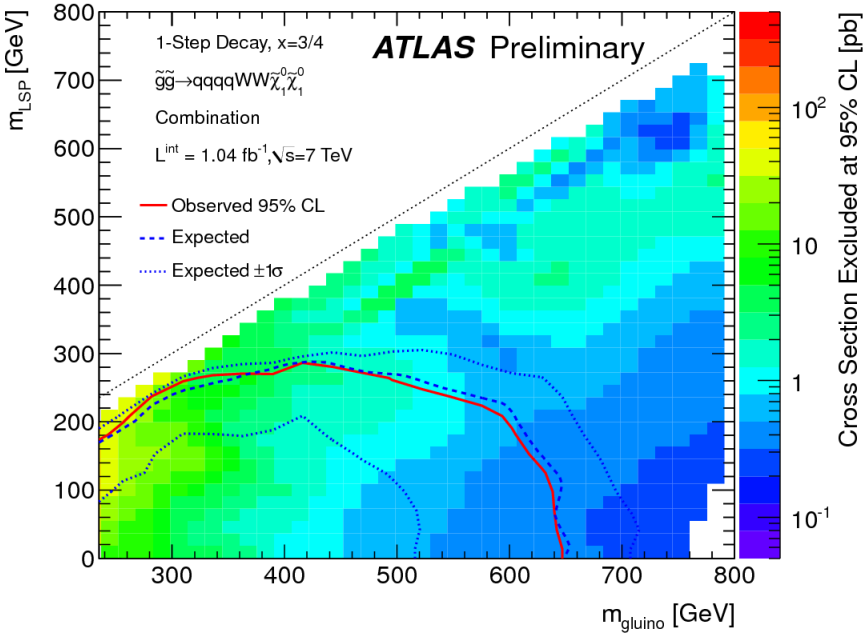


One Lepton + Jets + Missing E_T

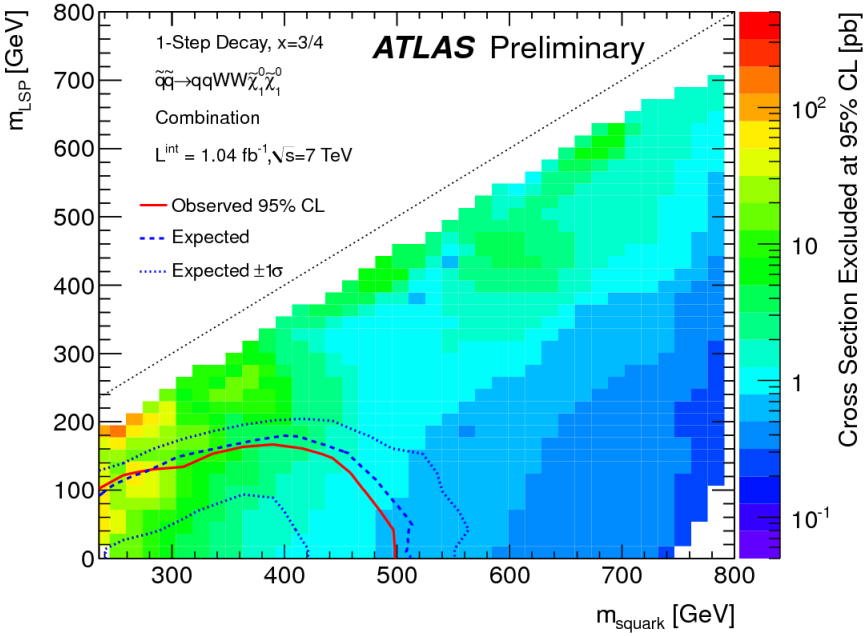
Update

SUSY11

Simplified model:
gluino → chargino → neutralino



Simplified model:
squark → chargino → neutralino



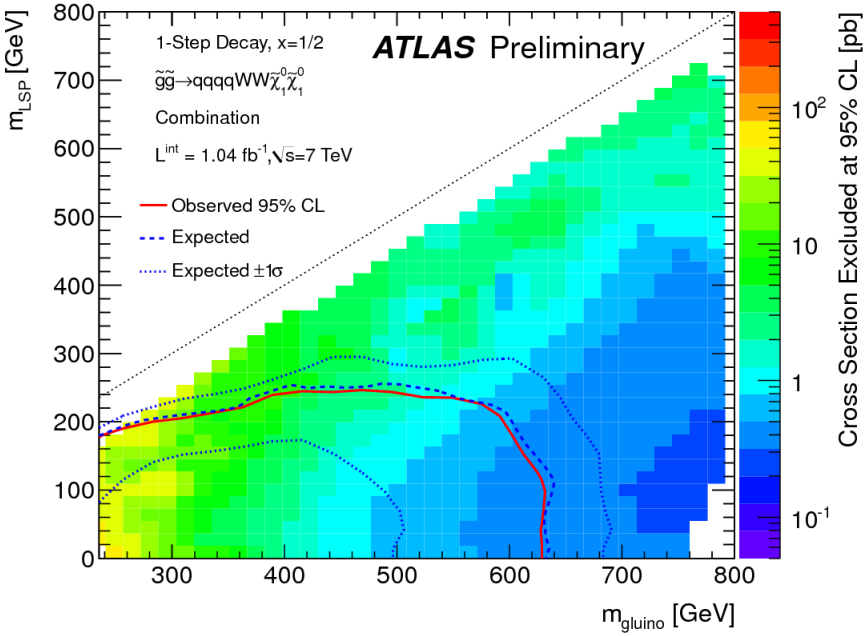
$$x = (m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^0}) / (m_{\tilde{q}/\tilde{g}} - m_{\tilde{\chi}^0})$$

One Lepton + Jets + Missing E_T

Update

SUSY11

Simplified model:
gluino → chargino → neutralino



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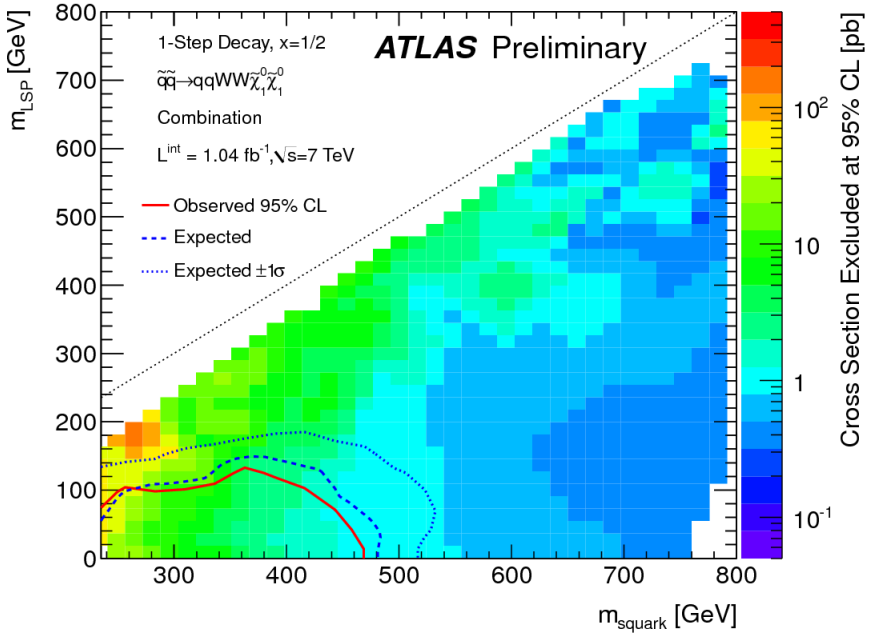

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One Lepton + Jets + Missing E_T

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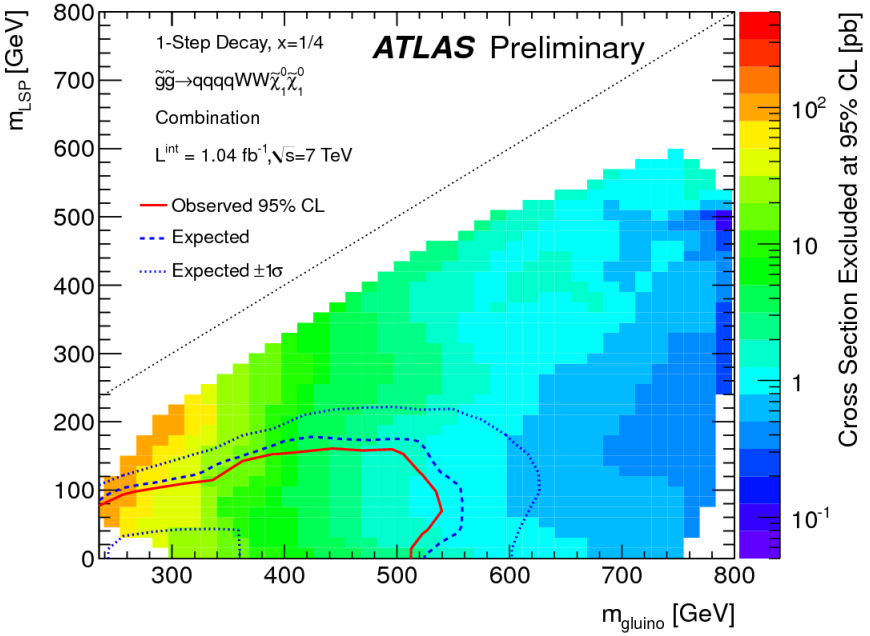

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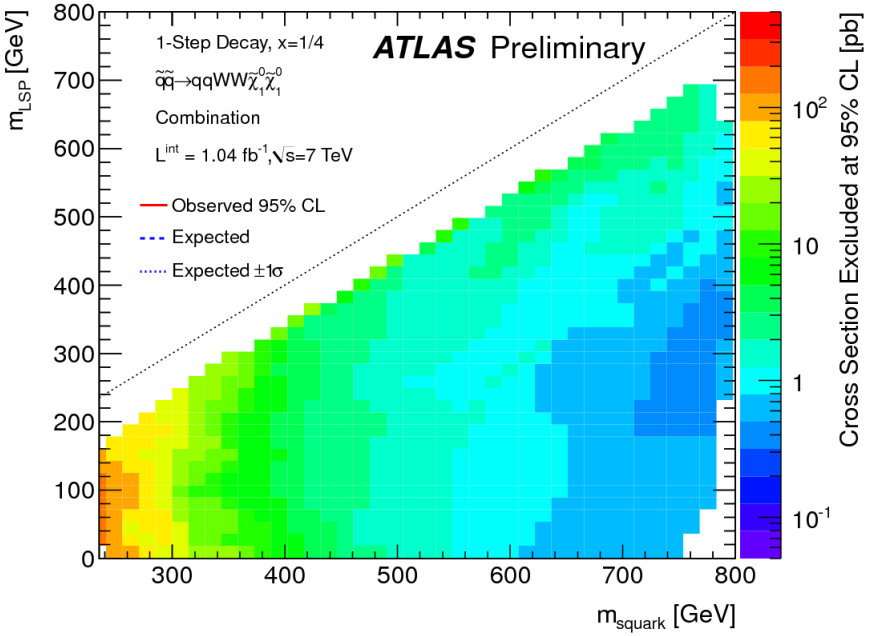


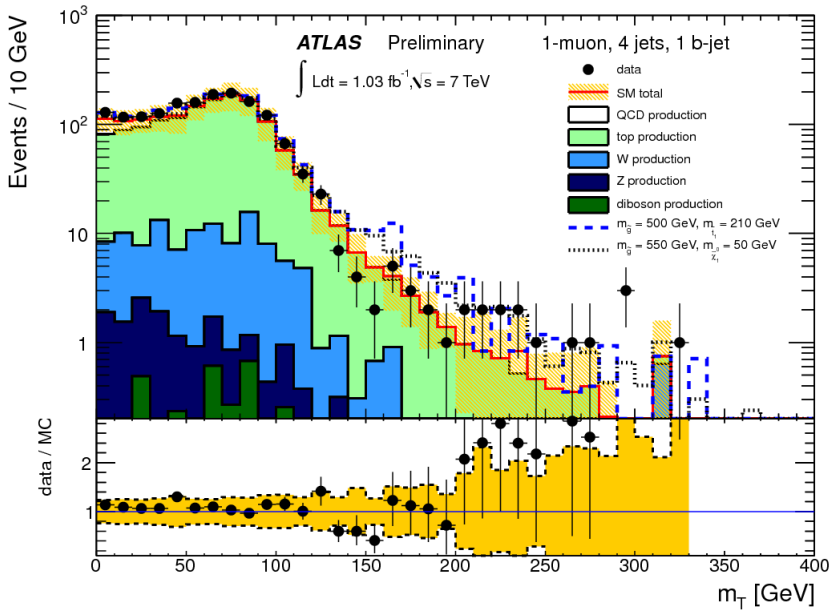
$$x = (m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^0}) / (m_{\tilde{q}/\tilde{g}} - m_{\tilde{\chi}^0})$$

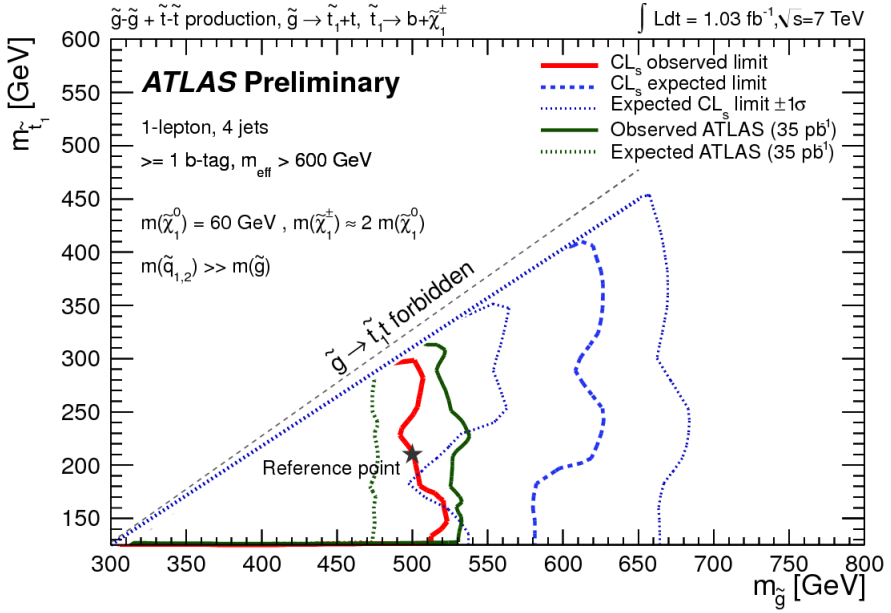
One Lepton + b-jets + Missing E_T

Update LP2011

- 3rd generation is special: has to be light to stabilize the Higgs
- selection similar to one lepton + 4 jets + missing E_T plus 1 b-tags
- signal region defined by missing E_T > 80 GeV, m_T> 100 GeV and m_{eff} > 600 GeV

Phenomenological MSSM:
BR($g \rightarrow t_1 t \rightarrow tb\chi^{\pm}_1$) = 100%





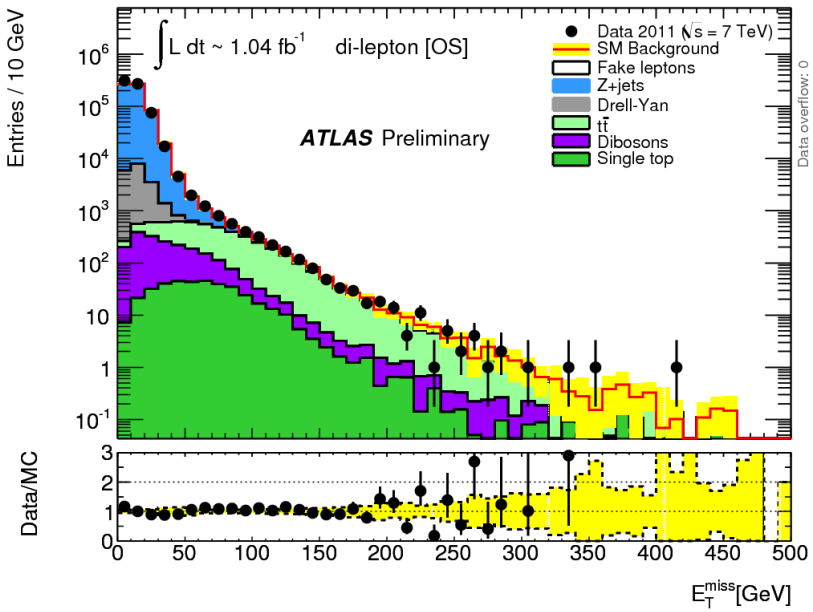
Two Lepton + Jets + Missing E_T

Update LP2011

- 2 leptons from chargino/neutralino decays
- 3 analyses, searching for dilepton events:
  - opposite sign (OS) → a),b),c),d)
  - same sign (SS) → a),b)
  - with flavour subtraction (FS) → c),d)
- selection: exactly 2 isolated leptons with

$$a)\ \tilde{\chi}_i^0 \to l^{\pm}\nu\tilde{\chi}_j^{\mp}$$
$$b)\ \tilde{\chi}_i^{\pm} \to l^{\pm}\nu\tilde{\chi}_j^0$$
$$c)\ \tilde{\chi}_i^0 \to l^{\pm}l^{\mp}\tilde{\chi}_j^0$$
$$d)\ \tilde{\chi}_i^{\pm} \to l^{\pm}l^{\mp}\tilde{\chi}_j^{\pm}$$

ee: p_T > 25/20 GeV
eμ: p_T > 25/10 GeV
μe: p_T > 20/20 GeV
μμ: p_T > 20/10 GeV
and M_{ll} > 12 GeV



Opposite sign:
- three signal region ➔E_T^{miss} / jets
- main background ➔top pairs, Z+jets

Same sign:
- two signal region ➔E_T^{miss} / jets
- main background ➔fake leptons from jets, opposite sign leptons with charge mismeasurement

Two Lepton + Jets + Missing E_T

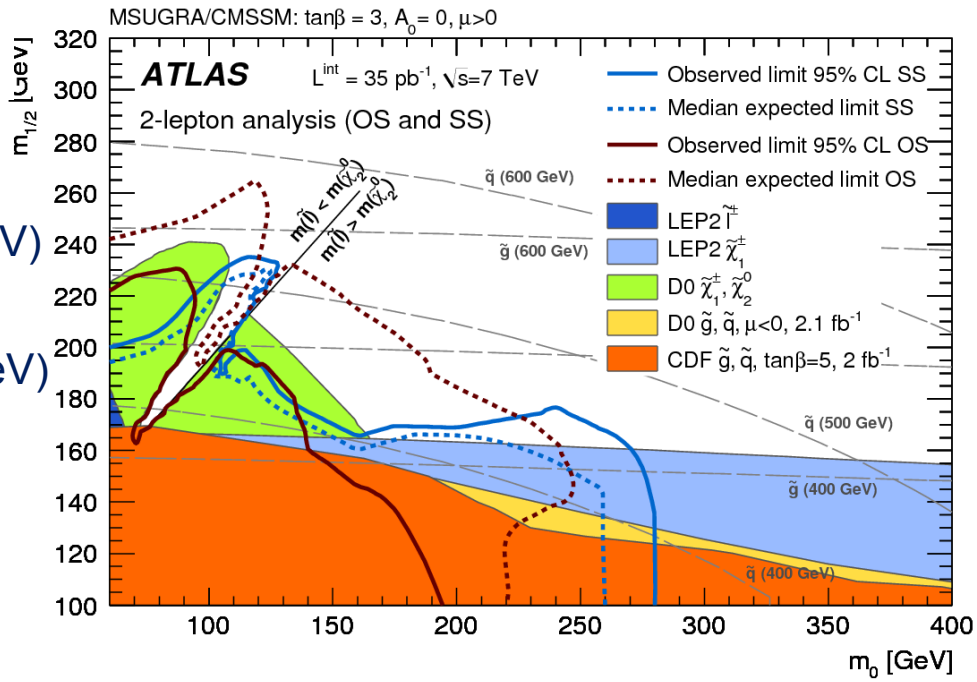
Update LP2011

- No excess above the SM predictions seen in different signal regions
- 95% C.L. upper limits on
  cross section of non-SM processes × acceptance × efficiency:

	Background	Obs.	95% C.L.
OS-SR1	$15.5 \pm 1.2 \pm 4.4$	13	9.5 fb
OS-SR2	$13.0 \pm 1.8 \pm 4.1$	17	15.2 fb
OS-SR3	$5.7 \pm 1.1 \pm 3.5$	2	5.0 fb
SS-SR1	$32.6 \pm 4.4 \pm 4.4$	25	10.2 fb
SS-SR2	$24.9 \pm 4.1 \pm 6.6$	28	20.3 fb

- 2010 result:
  - OS cross section limit (MET > 150GeV)
    ee: 90 fb, eμ: 220 fb, μμ: 210 fb
  - SS cross section limit (MET > 100 GeV)
    70 fb

For flavour subtraction see talk by Sky French [9B Thu]

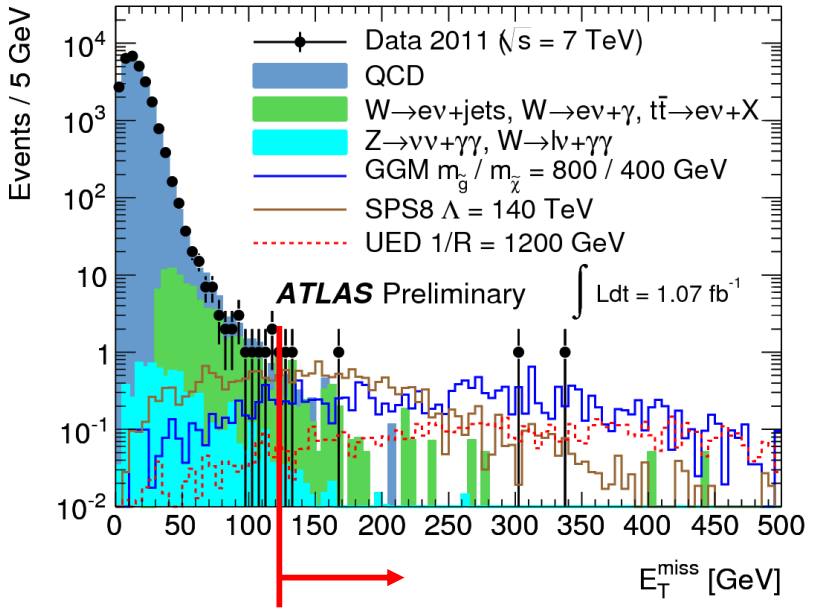


Diphoton + Missing E_T

Update

SUSY11

- Gauge Mediated SUSY Breaking (GMSB)
  - the very light gravitino is the LSP
  - event topology defined by next to lightest sparticle (NLSP)
  - large parameter space has neutralino NLSP: neutralino decays to photon and gravitino
- final state: diphoton (+ jets) + MET
  - 2 photons (E_T > 25 GeV)
  - missing E_T > 125 GeV
  - QCD and EW background estimated from control regions, irreducible background from MC
- result:
  - observed events: 5
  - expected events: 4.1 0.6 1.6



Diphoton + Missing E_T: Interpretation

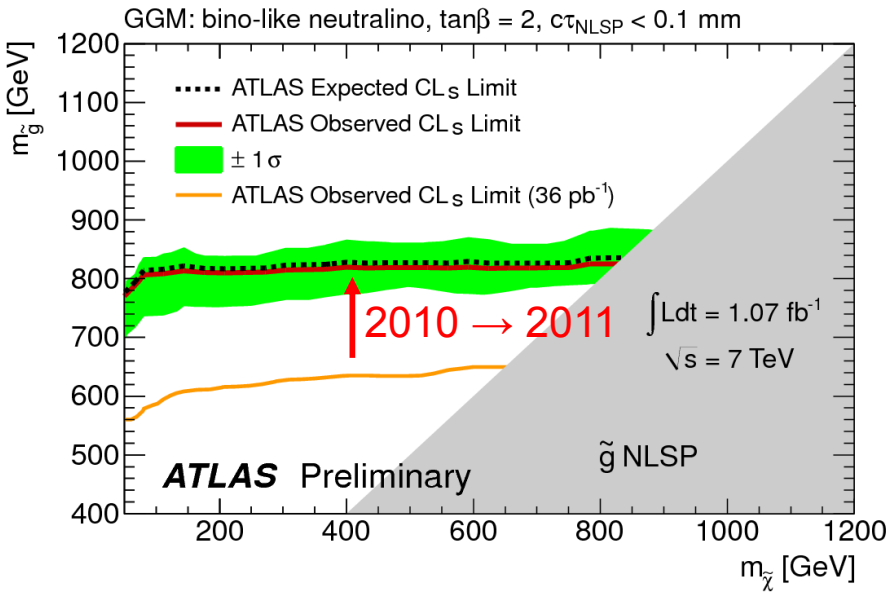
Update SUSY11

> General Gauge Mediation (GGM)

- simplified model with three sparticles:

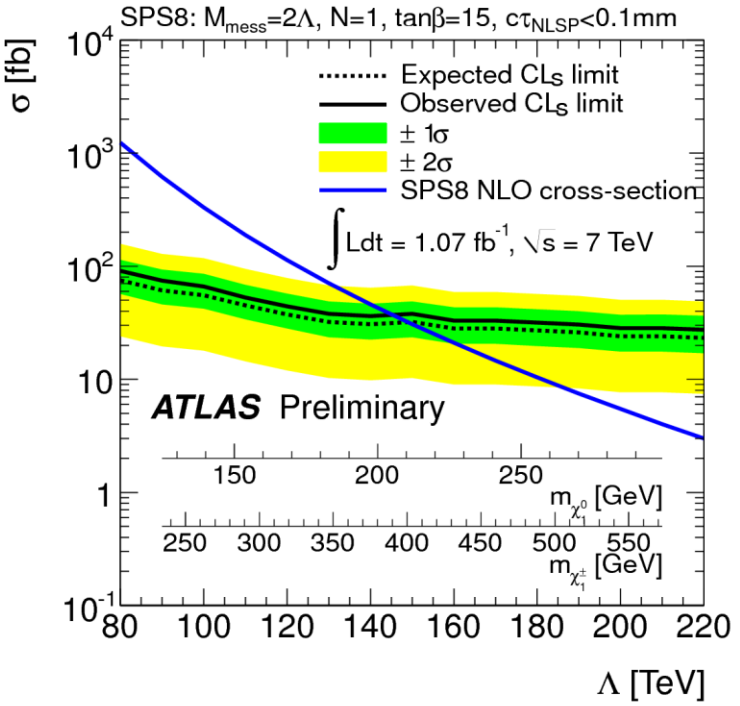
  Gluino for production
  Bino-like neutralino as NLSP

- m(gluino) < 776 GeV
  for m(neutralino) = 50 GeV



> minimal GMSB / SPS8 slope

- full mass spectrum
- first time considered at the LHC
- Λ < 145 TeV excluded



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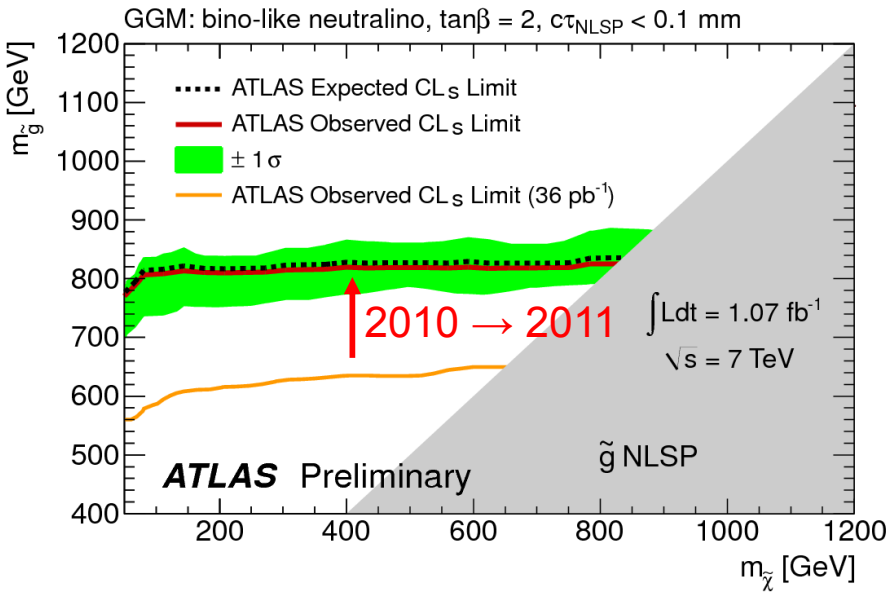
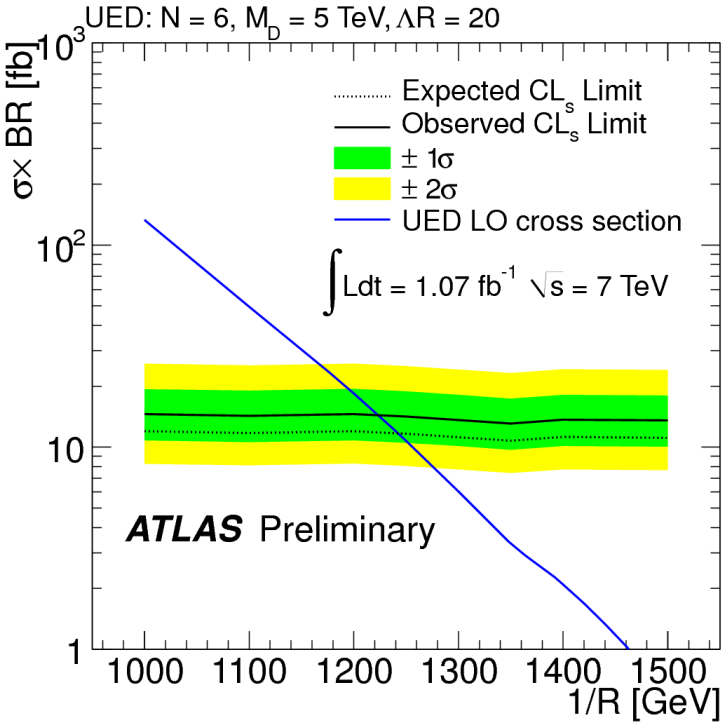


> Universal Extra Dimension (UED)

- mass spectrum similar to SUSY
- 1/R < 1224 GeV excluded



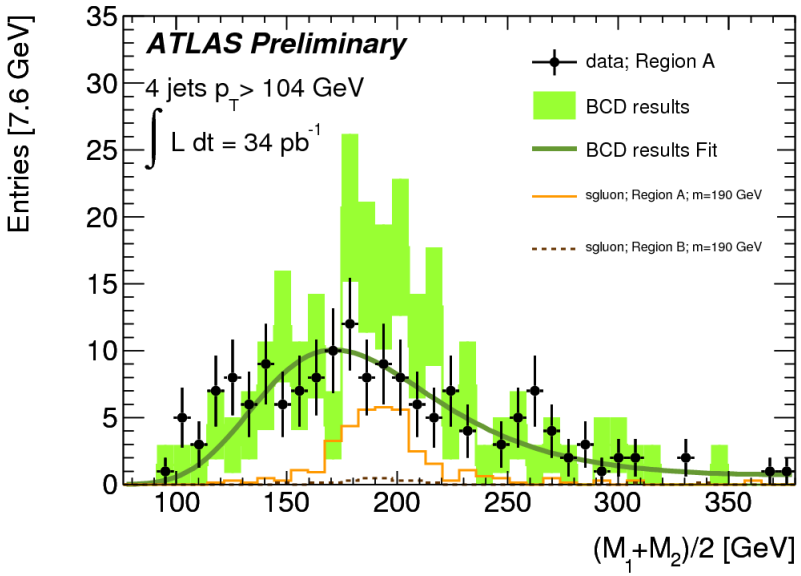
Search generic enough for different models!

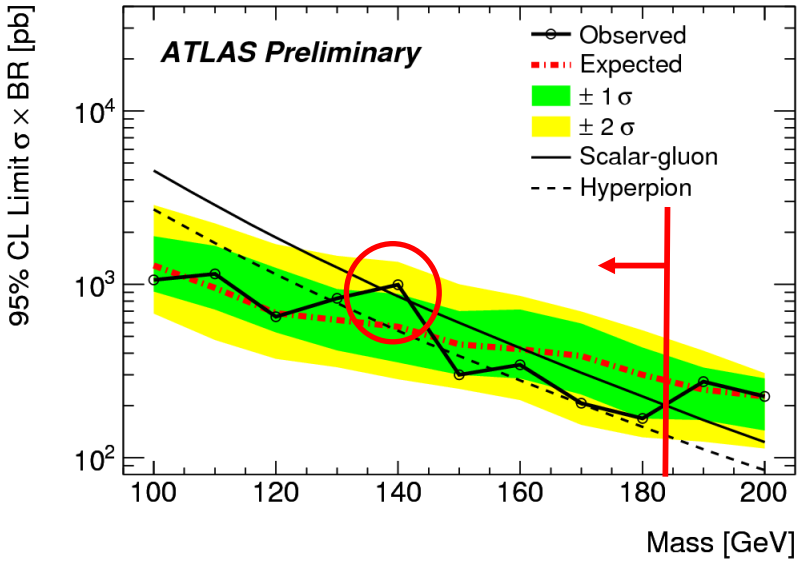
Other SUSY searches

Massive Colored Scalars in Four Jets

New SUSY11

- pair production of scalar gluons (sgluon) which decay into two jets each (extended SUSY) or hypercolor as SM extension
- selection:
  - 4 jets (p_T > 0.55 x sgluon mass), sgluon mass > 100 GeV
  - low threshold trigger for four jets only available in 2010
  - pair jets into sgluon candidates based on $\Delta R \sim 1$, reject events with $\Delta R_{jj} > 1.6$
  - require similar masses

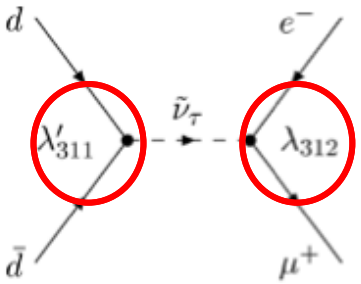


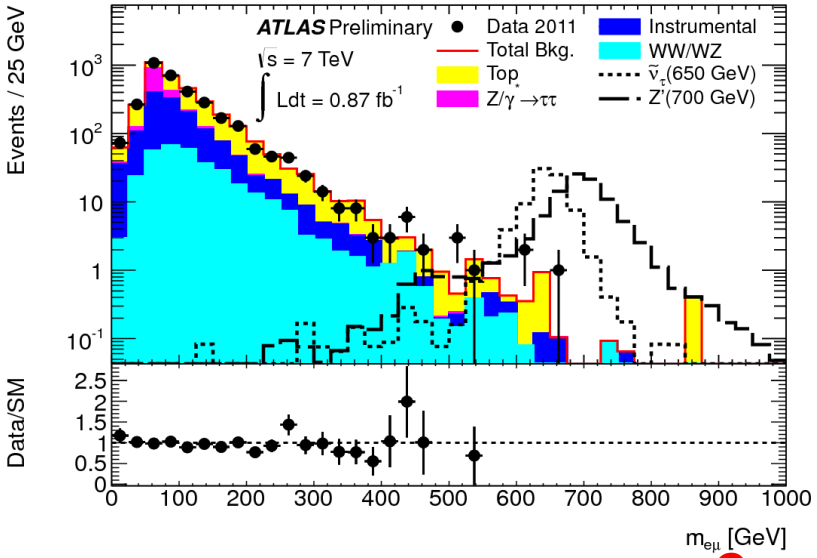


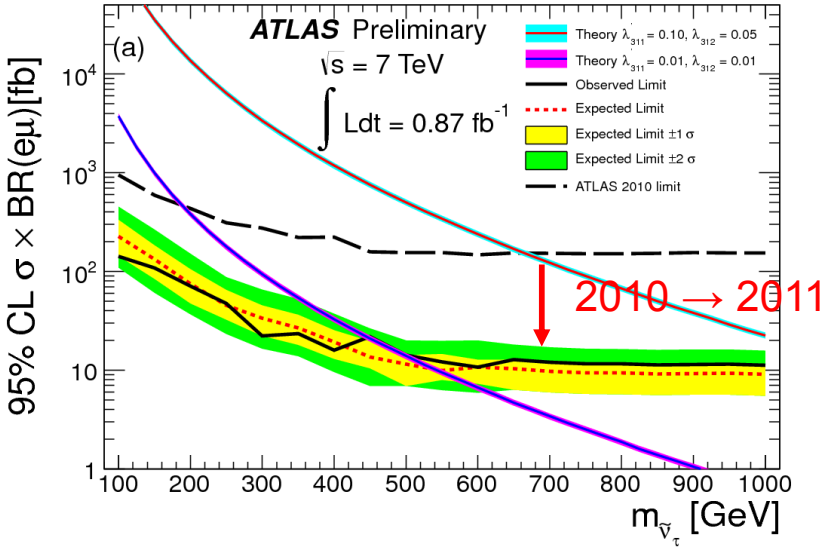
e Resonances (and RPV search)

Update EPS 2011

- search for electron and muon of opposite charge (R-parity violating decay of $\nu_\tau \rightarrow e\mu$)
  - isolated electron (p_T > 25 GeV) + isolated muon (p_T > 25 GeV)
  - no missing E_T cut
  - background from top pairs, single top, WW, WZ, ZZ, Z→tt rely on Monte Carlo, QCD and W/Z+ jets estimated from data with "loose-tight matrix method"
  - no deviation from SM in $m_{e\mu}$ distribution





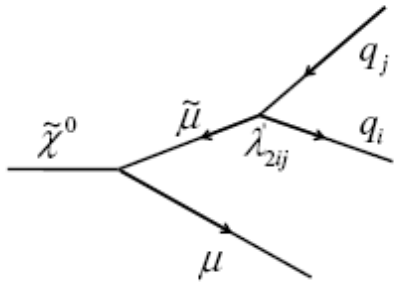


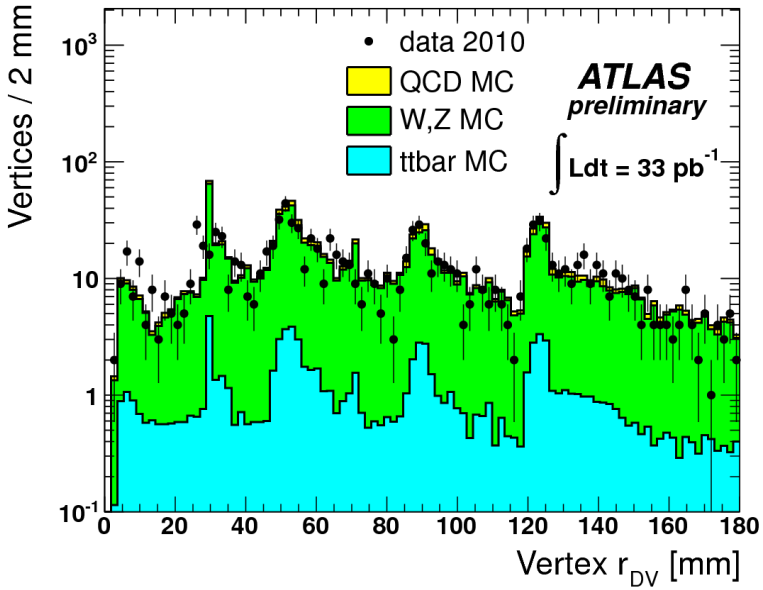
Can also interpreted as heavy boson → eμ

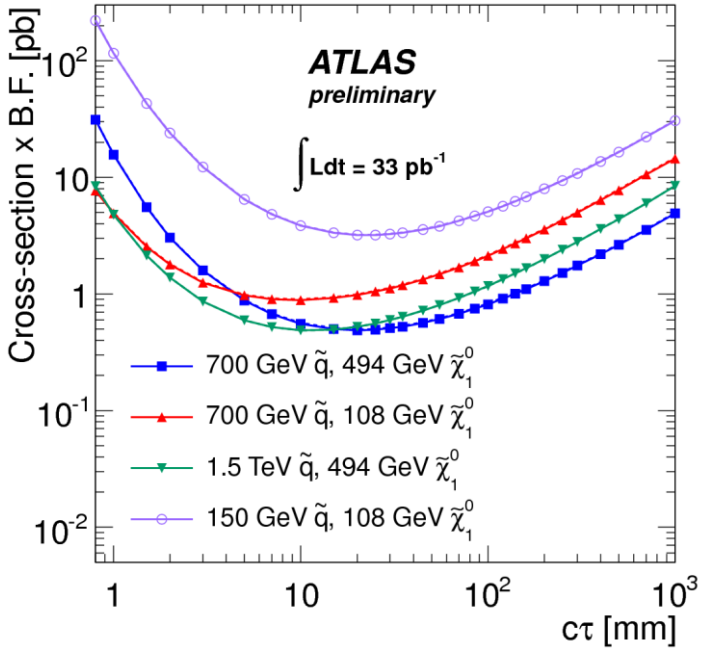
RP-Violation SUSY: Displaced Vertices

New EPS 2011

- look for heavy medium-lived particles in the inner tracker
- reconstruct vertices even far out of the beam-pipe, in association with a high-p_T muon (p_T > 45 GeV)
- requires good understanding of tracking, detector passive material







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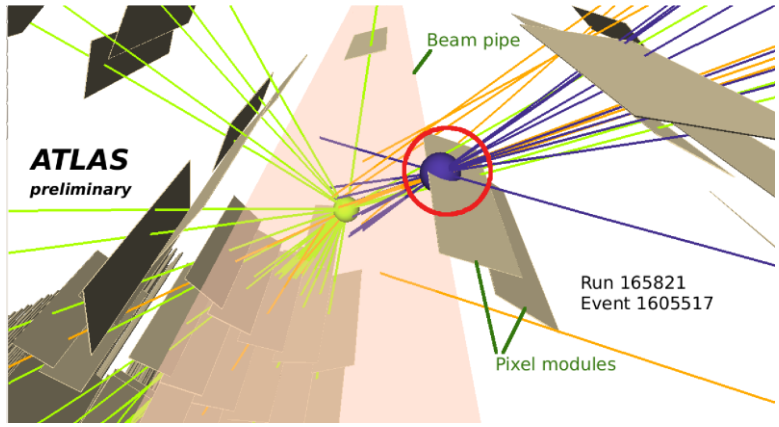
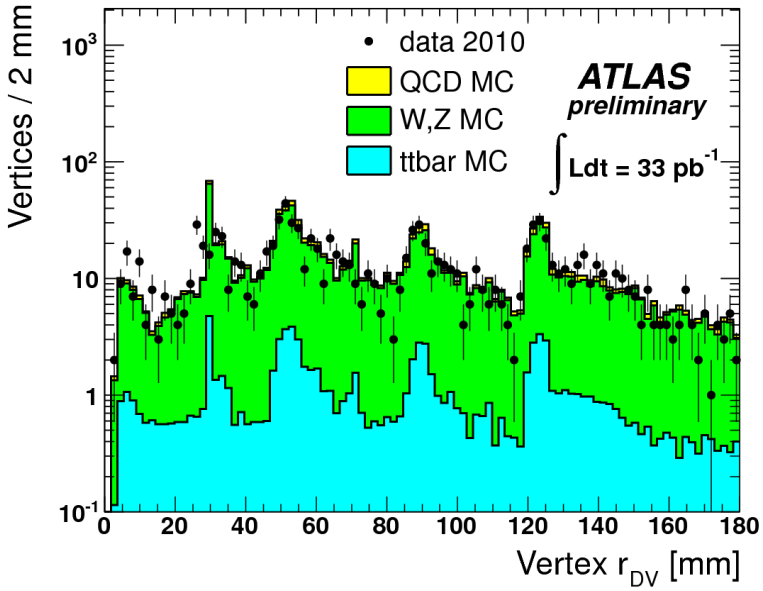
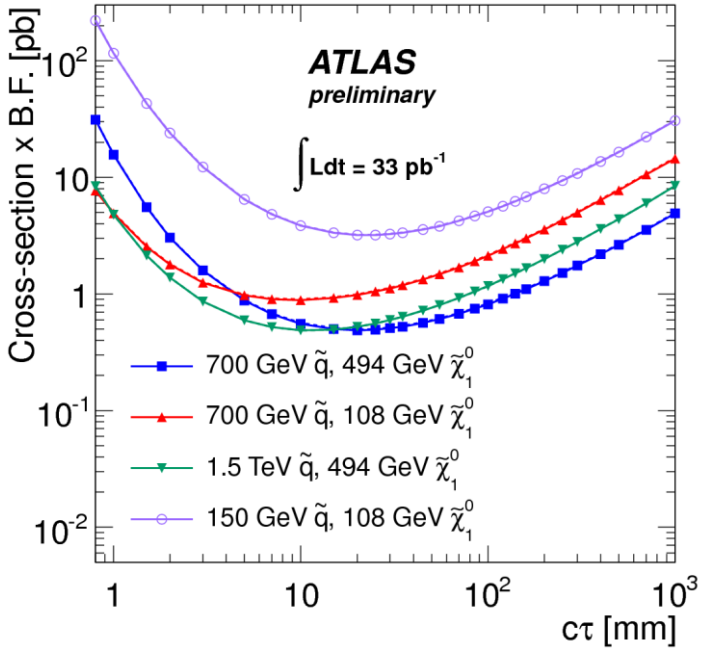
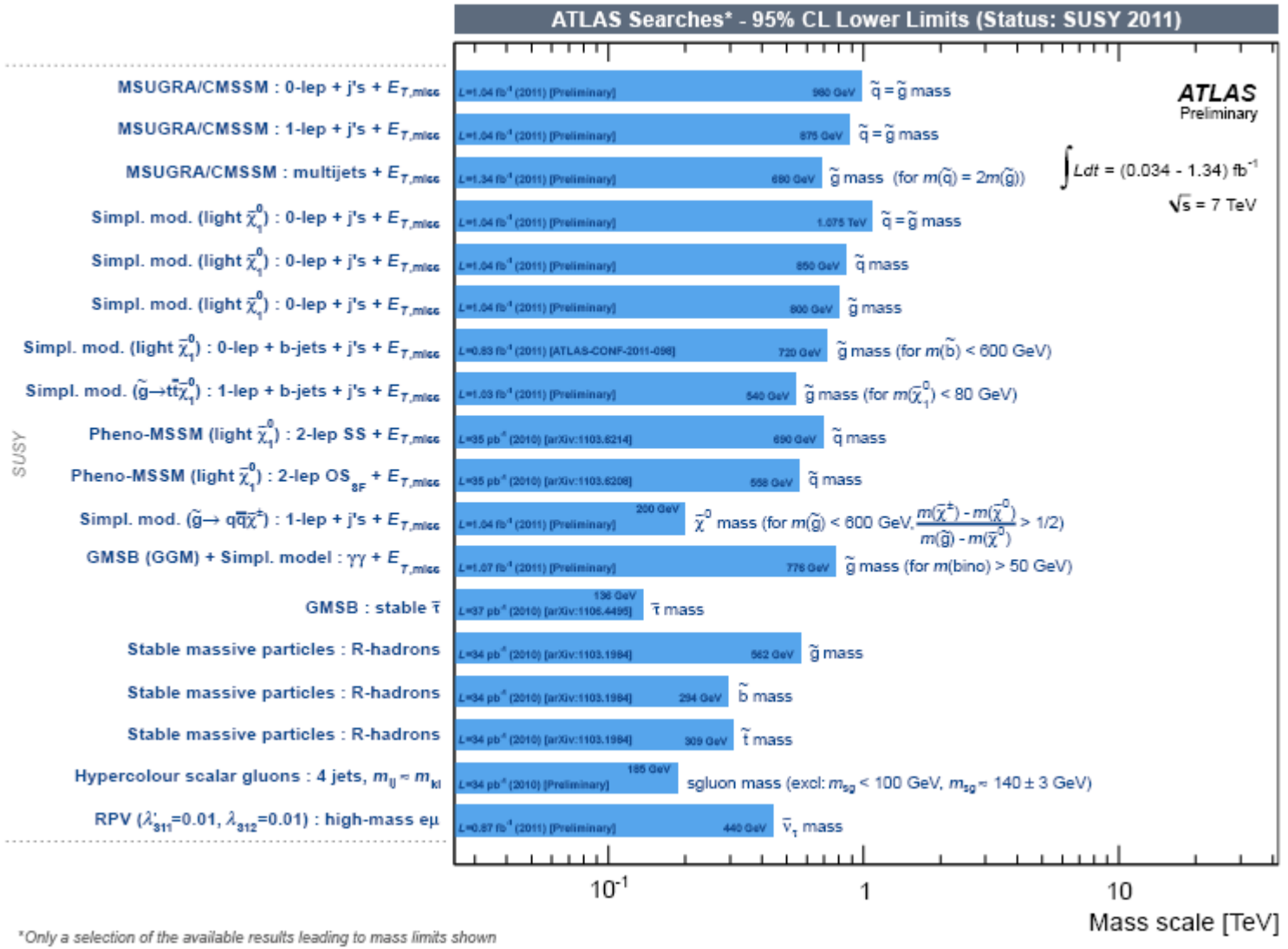






Summary of ATLAS SUSY Searches



*Only a selection of the available results leading to mass limits shown

Conclusion and Outlook

- ATLAS has produced an impressive number of papers/conference notes using the 2010 and 2011 data
- in the channels searched so far, no significant excess above the Standard Model was found
- SUSY was not “just around the corner”
- several limits have surpassed those from Tevatron/LEP
- besides MSUGRA/CMSSM also simplified models considered
- more data still to come in 2011 (already around 2.5 fb^{-1} on tape) and then there is 2012

Related Presentations at SUSY11

- Michael Flowerdew [5C Tue]: Search for supersymmetry in final states with jets and missing transverse energy with the ATLAS detector
- Takashi Yamanaka [6D Tue]: Search for supersymmetry in final states with b-jets and missing transverse energy with the ATLAS detector
- Sophio Pataraia [8D Thu]: Search for supersymmetry in final states with one lepton, jets and missing transverse energy with the ATLAS detector
- Sky French [9B Thu]: Search for supersymmetry in final states with multiple leptons and missing transverse energy with the ATLAS detector
- Jovan Mitrevski [5C Tue]: Search for supersymmetry in final states with photons and missing transverse energy with the ATLAS detector
- Emma Torro Pastor [9B Thu]: Search for R-partity violating supersymmetry with the ATLAS detector
- Josh Cogan [8D Thu]: Search for supersymmetry in final states with measurable lifetime with the ATLAS detector
- Junjie Zhu [6D Tue]: Search for supersymmetry via resonant final states with the ATLAS detector

Backup

Two Lepton + Jets + Missing ET: Flavour Subtraction

Update

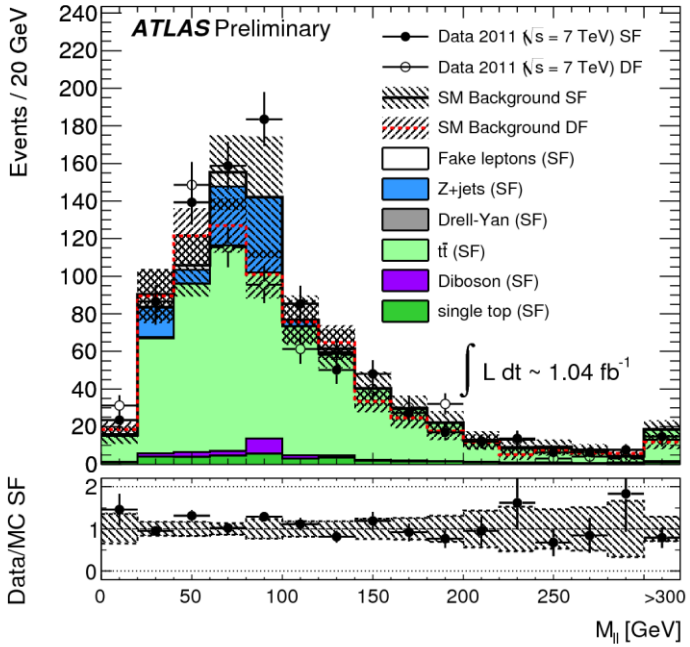
LP2011

- searches for excess of same flavour-opposite sign lepton pairs over different flavour-opposite sign:
- define the variable: where β is the ratio of e,μ efficiencies×acceptance and τ_e,τ_μ are trigger efficiencies

$$S = \frac{N(e^{\pm}e^{m})}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^{\pm}\mu^{m})}{(1-(1-\tau_e)(1-\tau_\mu))} + \frac{\beta N(\mu^{\pm}\mu^{m})}{(1-(1-\tau_\mu)^2)}$$

- three signal region based on missing E_T, number of jets and m_{ll} veto
  - SR1: SR2: SR3:
- apart from Z/γ* sources no excess is expected in SM
- SF-OF subtraction allows to cancel systematic uncertainties

	$\mathcal{S}_{obs}$	$\bar{\mathcal{S}}_b$	RMS
FS-SR1	131.6±0.6(sys)	126.5±23.5±17.2	49.9
FS-SR2	142.2±0.6(sys)	70.0±23.2±16.8	49.1
FS-SR3	-3.1±0.0(03)(sys)	0.4±1.2±1.2	4.6



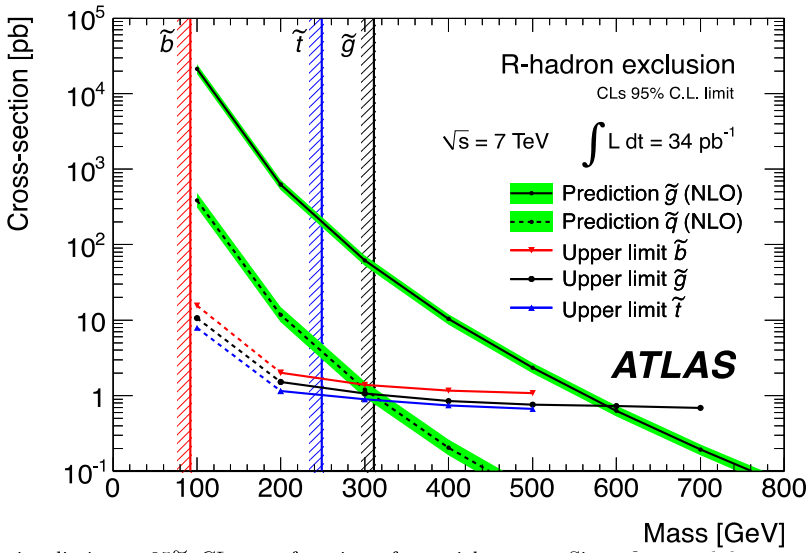
Search for Slow Particles

- Slow, Massive and Long Lived Particles (SMP, LLP) are predicted in several SUSY models (and in other BSM scenarios)
  - stable → ct ≥ size of detector (lifetimes ranging across many orders of magnitude!).
  - Produced with b<1 (signature is a slow object loosing energy mainly by ionization),
- In SUSY, an example are coloured sparticles hadronising into R-hadrons (bound hadronic states of a coloured sparticle, squark or gluino, and light quarks or gluons)
- 2 analyses in ATLAS to study slow particles:

1) search for R-hadrons or long-lived sleptons reaching Muon Spectrometer (MS)
- Sleptons search uses ID+MS, R-hadrons search only MS, in both determine β_{MS} **and m= p/βγ**
- Background estimate → exploit the lack of correlations between β_{MS} and momentum

2) search for charged or neutral R-hadrons, relying only on ID and Tile Calorimeter
- Search uses: long time of flight in Tile and large dE/dx in Pixel detector → in both determine **β and m= p/βγ**
- Background estimate → exploit the lack of correlations between dE/dx, β_{tile} and momentum

Search for Slow Particles



95% CL Exclusion from search 2):

Gluino masses <562-586 GeV (dep. on the model of hadronic scattering in matter)

Stop masses <309GeV

Sbottom masses <294 GeV (first dedicated search for sbottom R-hadrons at hadron colliders)

95% CL Exclusion from search 1):

Gluino masses <530-544 GeV, dep. on the model (with gluino as lightest LLP in Split-SUSY)

Stau masses <136 GeV (with light stau as lightest LLP in GMSB)